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A NEW PROOF OF THE VARIABILITY OF THE SUN, BASED ON MOUNT WILSON OBSERVATIONS

551. 521

By C. G. ABBOT, Assistant Secretary

[Smithsonian Institution, Washington, June 21, 1926]

On returning from abroad, I find that a number of critical articles have appeared which seem to indicate great doubt, not only as to the existence of short-interval variations of the sun's radiation, but even of the longer-interval swings which seem to be exposed by the work of the Smithsonian Astrophysical Observatory. It is said that traces of yearly periodicity are found which lead to the hypothesis that the variations are due to terrestrial influences. It is said that the pyrheliometer observes so much sky around the sun that variations of the haziness of the sky introduce variations of solar constant determinations by no means negligible. It is said that the work at Mount Wilson, which continued over the summer and autumn months of many years, is so inaccurate, owing to terrestrial influences, that it may be discarded from consideration, and with it all applications which have been made of those results to weather conditions.[1] It is said that the computations and assumptions made in connection with the bolometric observations are so complex and doubtful that the variations which are found in the solar constant are more probably due to these than to real variations in the sun.

It would be easy to collect very extensive matter in rebuttal, after which the authors of the criticisms would doubtless again bring in a rejoinder, and so the controversy might go on indefinitely without convincing the authors on either side and leading the readers into a hopeless state of uncertainty. Fortunately, a very simple consideration has occurred to me which, it seems probable, may convince the critics of the variation of the sun that both long and short period fluctuations really exist, and that the work of Mount Wilson should not be rejected.

The new consideration may be understood by reflecting that if the observer could locate himself upon the moon he would need there only the pyrheliometer to follow the variations of the sun,[2] because there would be no screen interposing between him and its rays, and if instrumentally accurate his results would be real indications of the constancy or variability of the sun itself. In the actual conditions the observer is hindered by the presence of the ocean of atmosphere above him, which contains variable elements. If it were possible to confine observing to conditions in which these variable elements remained sensibly constant, the presence of the atmosphere would no longer be a hindrance to determining the variability of the sun. It would then become like a partially transparent screen, reducing, it is true, the solar rays, but reducing them in the same proportion on every day of observation. Let us consider whether this device can not be employed.

Between the years 1910 and 1920 the intensity of solar radiation was observed on many days of the summer and autumn months by means of two pyrheliometers mounted upon a single stand and read alternately, and usually by one or the other of two observers, C. G. Abbot and L. B. Aldrich. On numerous occasions during this interval these pyrheliometers were compared with the standard water-flow pryheliometer, and with various secondary pyrheliometers, which were also intercompared between themselves. As indicated in Volume IV of the Annals of the Astrophysical Observatory, this series of intercomparisons of pyrheliometers does not indicate fluctuations of consequence in the scale of readings of these instruments. During all this interval, bolometric observations were made on the same days with the pyrheliometric work, and there were determined from these spectrobolometric curves, by the method of Fowle, the total quantity of precipitable water between the observer and the limit of the atmosphere. This method, as is stated in Volume IV of the Annals of the Astrophysical Observatory, has been checked by Mr. Aldrich and Mr. Fowle with favorable results. In the use which I shall make of it here it is not, however, necessary to suppose that the actual quantities of precipitable water determined are strictly correct, because the application is limited to the determination of days of equal quantities of precipitable water. This merely means that the depth of certain great water vapor bands in the bolographs of the infra-red spectrum were substantially identical for equal air masses, and this is surely an indication that the total quantity of water in the atmosphere was for these days substantially equal.

Taking, then, this homogeneous body of pyrheliometric observations, I have limited myself in the present article mainly to the month of July. In this month the distance of the sun is so nearly uniform that it is not necessary for the present purpose to make corrections for solar distance. Any question of the yearly periodicity in the solar constant values is obviously eliminated.

The first question, then, is: Does the pyrheliometric work of Julys from 1910 to 1920 indicate that on some of these Julys the sun's radiation was more intense than on others?

To solve this question, I divided the observations as reported in Volume IV of the Annals of the Astrophysical Observatory into four groups. Group 1 contained only

[1] The reader may here profitably refer to the MONTHLY WEATHER REVIEW for July, 1925, p. 286, quotation in second column, not omitting the seventh sentence.

[2] See MONTHLY WEATHER REVIEW, July, 1925, p. 290, the first two paragraphs under "Analysis of Pyrheliometer Readings" * * *, etc.

See also MONTHLY WEATHER REVIEW, December, 1925, p. 527, first paragraph of second column.

those days in which the apparent atmospheric transparency, as determined by the pyrheliometer alone, lay between narrow limits, whose mean was approximately 0.904, and when the precipitable water lay between narrow limits averaging approximately 5 mm. Group 2 contained only days in which the atmospheric transparency, still within narrow limits, was somewhat less and the precipitable water, also within narrow limits, was approximately 12 mm. Group 3 contained only those days in which the atmospheric transparency, still between narrow limits, was again less, and the precipitable water, also between narrow limits, was approximately 20 mm. Group 4 contained the days which were rejected, either because the precipitable water much exceeded 20 mm., or the transparency, if falling within one of the groups, was accompanied by precipitable water conditions which did not fall in the same group. There remained, after this rejection, numbers of days which are given in Table 2, which follows.

To illustrate the grouping, I give in Table 1 the arrangement of data for the month of July, 1915. Values have been printed in three types for a purpose which will appear later.

TABLE 1.—*Sample grouping*

Date	Ppt. H_2O	App. "a"	Pyrh.[1] m=1.5	Solar constant E'_0
	Mm.			
5	*4.9*	*0.896*	*2.855*	*1.930*
16	**5.5**	**.901**	**2.935**	**1.976**
17	**3.6**	**.906**	**2.940**	**1.979**
26	*7.9*	*.904*	*2.842*	*1.950*
27	**4.1**	**.906**	**2.923**	**1.943**
28	**3.5**	**.908**	**2.930**	**1.936**
29	*7.0*	*.900*	*2.840*	*1.934*
31	*6.9*	*.907*	*2.805*	*1.906*
Mean	5.4	.903	2.884	1.944
10	*14.8*	*.895*	*2.737*	*1.929*
11	11.7	.897	2.800	1.947
12	12.4	.891	2.790	1.947
13	*11.4*	*.881*	*2.765*	*1.959*
14	**8.6**	**.895**	**2.860**	**1.949**
18	**10.2**	**.909**	**2.857**	**1.960**
Mean	11.5	.895	2.802	1.948
3	*18.3*	*.894*	*2.690*	*1.915*
7	21.9	.884	2.710	1.968
8	21.2	.888	2.710	1.955
9	**15.6**	**.887**	**2.764**	**1.934**
Mean	19.2	.888	2.719	1.943

[1] To reduce to calories, multiply by 0.511.

TABLE 2.—*Summary of observations*

Year	Group	Number of days	July dates	Group weights	Ppt. H_2O		Apparent "a"		Pyrheliometer at air mass 1.5		Solar constant E'_0		Ratio to general mean of group	
					Mean	Range	Mean	Range	Value	Range	Mean	Range	Pyr.	S. C.
					Mm.	*Mm.*							$1\pm\%$	$1\pm\%$
1910	1	6	2, 3, 4, 5, 8, 28	24	4.9	4.2	0.902	0.011	1.461	0.110	1.899	0.070	−1.02	−2.01
	2	3	6, 7, 15	9	11.7	6.6	.897	.000	1.395	0.113	1.909	0.071	−1.06	−1.34
	3	1	19	2	22.0		.879		1.360		1.963		−0.08	+0.41
			Total	35							Weighted mean		−0.95	−1.70
1911	1	6	1, 4, 5, 24, 30, 31	24	4.8	3.4	.904	.011	1.468	0.082	1.927	0.085	−0.54	−0.57
	2	2	7, 12	6	9.7	1.2	.901	.009	1.388	0.009	1.895	0.088	−1.56	−2.06
	3	2	13, 20	4	22.0	1.9	.885	.016	1.333	0.024	1.888	0.086	−2.06	−3.44
			Total	34							Weighted mean		−0.60	−1.17
1914	1	3	27, 28, 29	12	6.8	3.8	.903	.002	1.462	0.041	1.947	0.047	−0.95	+0.46
	2	4	1, 2, 17, 26	12	13.2	7.6	.892	.008	1.398	0.046	1.949	0.039	−0.85	+0.72
	3	5	18, 19, 20, 21, 30	10	18.6	3.2	.878	.018	1.357	0.066	1.967	0.127	−0.30	+0.62
			Total	34							Weighted mean		−0.72	+0.60
1915	1	8	5, 16, 17, 26, 27, 28, 29, 31	32	5.4	4.4	.903	.012	1.474	0.069	1.944	0.073	−0.14	+0.31
	2	6	10, 11, 12, 13, 14, 18	18	11.5	6.2	.895	.028	1.432	0.063	1.948	0.031	+1.56	+0.67
	3	4	3, 7, 8, 9	8	19.2	6.3	.888	.010	1.389	0.057	1.943	0.053	+2.06	−0.62
			Total	58							Weighted mean		+0.69	+0.30
1916	1	8	3, 4, 5, 6, 17, 18, 25, 28	32	5.8	3.2	.905	.009	1.480	0.040	1.945	0.022	+0.27	+0.36
	2	4	1, 10, 12, 15	12	11.6	4.8	.896	.015	1.399	0.064	1.908	0.048	−0.80	−1.39
	3	2	11, 31	4	17.0	0.7	.887	.020	1.367	0.025	1.929	0.027	+0.44	−1.33
			Total	48							Weighted mean		+0.02	−0.22
1917	1	2	8, 9	8	4.2	0.8	.898	.006	1.475	0.038	1.929	0.017	−0.07	−0.47
	2	0												
	3	4	5, 6, 7, 19	8	16.8	6.0	.878	.017	1.396	0.028	2.007	0.088	+2.58	+2.67
			Total	16							Weighted mean		+1.26	+1.11
1918	1	6	11, 24, 25, 26, 27, 28	24	3.4	3.0	.902	.023	1.492	0.066	1.960	0.104	+1.10	+1.14
	2	6	6, 14, 15, 21, 22, 23	18	12.3	4.5	.895	.016	1.413	0.027	1.943	0.051	+0.21	+0.41
	3	4	4, 5, 9, 29	8	20.1	3.6	.877	.026	1.352	0.071	1.959	0.114	−0.66	+0.20
			Total	50							Weighted mean		+0.44	+0.73
1919	1	4	1, 29, 30, 31	16	5.0	4.9	.901	.015	1.493	0.060	1.955	0.060	+1.15	+0.88
	2	4	2, 3, 6, 7	12	11.9	3.3	.885	.019	1.414	0.013	1.944	0.057	+0.28	+0.47
	3	3	10, 11, 14	6	23.8	4.6	.876	.032	1.322	0.078	1.952	0.019	−2.87	−0.15
			Total	34							Weighted mean		+0.13	+0.55
1920	1	5	9, 11, 12, 13, 19	20	6.3	4.2	.903	.019	1.475	0.027	1.942	0.022	−0.07	+0.21
	2	7	8, 10, 14, 17, 18, 25, 26	21	13.6	5.0	.885	.015	1.414	0.023	1.934	0.060	+0.28	−0.06
	3	2	24, 29	4	21.0	2.1	.881	.006	1.338	0.064	1.934	0.008	−1.70	−1.28
			Total	45							Weighted mean		−0.52	−0.49

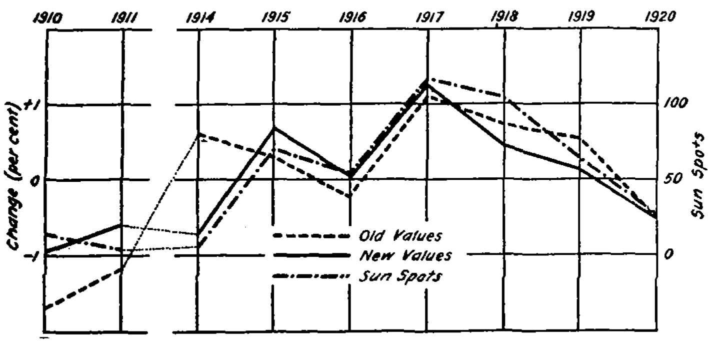
On each of the days included in groups 1, 2, and 3 the reading of the pyrheliometer as it would have been found at air mass 1.5 was determined by logarithmic interpolation from the series of observations reported in Volume IV of the Annals, and on each of the days the value of the solar constant of radiation, E'_0, as given in

Volume IV of the Annals, was taken out. Mean values for the pyrheliometry at air mass 1.5 and for the solar constant were obtained for each group in each month.

It was necessary to omit the years 1912 and 1913 in this analysis, because the volcanic dust thrown up in the great eruption of Mount Katmai had rendered the atmosphere so turbid that, although precipitable water conditions suitable to the groups were available, they were not accompanied by transmission coefficients which fitted at all. Accordingly, these years were rejected from the study.

Readers will perceive that errors due to extraneous radiation from the sky and toward the sky around the sun seen by the pyrheliometer are minimized in this method of treatment because the brightness and transparency of the atmosphere were practically identical for all days and years within the same group, and because since all observations are taken in July the outgoing radiation from the instrument reached atmospheric regions of nearly the same temperature from year to year. Also errors from changing transparency during a day are minimized because, first, no exceptional days were included, and, second, because all observations relate to one and the same moment of the day and not, as in the long method bolometry, to a period of several hours.

It was considered that the individual days of the several groups should receive different weights, and after consideration, the convention was adopted that individual days falling in group 1 should receive weight 4; those in group 2, weight 3; and those in group 3, weight 2, respectively. With this convention, and in consideration of the numbers of days in the several groups, there were obtained for the whole interval 1910 to 1920,[3] group means both of the pyrheliometry at air mass 1.5 and of the solar constant E'_0. See Table 4 below. From these group means were taken the percentage departures of the group means for the several Julys, as indicated in Table 2. Finally, in order to get single values representing the pyrheliometric and bolometric result of each July, the weighted mean of the percentage departures for the three groups was determined, as noted in Table 2, and which are summarized as the results of the investigation in Table 3. The results are also shown graphically in the accompanying illustration.



It will be perceived that with the exception of July, 1914, there is a very close agreement between the bolometric and pyrheliometric results, and that both are in strong correlation with the variation of the sun-spot numbers. I have also tried the month of August for the same interval, in the same manner, and have obtained results of the same general import, though they also indicate a departure in the same sense for the bolometric result of 1914.[4] Thus, this new and simple method confirms the result formerly obtained from Mount Wilson solar constant determinations to the effect that in a term of years the intensity of solar radiation increases with sun-spot numbers. The new work supports the solar constant values both as to the times and magnitudes of the change.

TABLE 3.—*Long-interval solar variations, July*

(Mount Wilson Data)

Year	Percentage departures: Pyrh. M=1.5	Percentage departures: Solar constant E'_0	Sun-spot numbers
1910	−0.95	−1.70	14
1911	−0.60	−1.17	3
1914	−0.72	+0.60	5
1915	+0.69	+0.30	71
1916	+0.02	−0.22	53
1917	+1.26	+1.11	117
1918	+0.44	+0.73	105
1919	+0.13	+0.55	64
1920	−0.52	−0.49	26

In the following Table 4, are given the group means for the solar constant (E'_0) and pyrheliometry ($M=1.5$) for the whole series of Julys and Augusts. In obtaining all the pyrheliometric values for August, I allowed for the variation in solar distance and computed the values for the same solar distance as of July 15, in order to fit them for use in Table 5, below.

TABLE 4.—*Group mean solar constant and pyrheliometric values*

Group	Solar constant E'_0			Pyrheliometry M=1.5		
	1	2	3	1	2	3
Mean values:						
July	1.938	1.935	1.955	1.476	1.410	1.361
August	1.937	1.942	1.957	1.471	1.391	1.318

It will be noted that the agreement of solar constant values for Groups 1 and 2 for July and August is as close as could be hoped for, but that in each case the mean for Group 3 is about 1 per cent higher than for the others. This, I am inclined to think, is a real indication that the solar constant values obtained on Mount Wilson on days of excessive haziness and humidity were made too high by reason of the influence of sky radiation. Doctor Dorno points out this source of error in the MONTHLY WEATHER REVIEW for December. We had become aware of it a good while before, and had taken measures to evaluate its magnitude and to eliminate it in future work. I hope to treat this matter more extensively in a forthcoming publication.

It is to be noted that in taking the mean monthly departures of the solar constant in Table 3 of this present communication, they are not comparable with the departures which could be taken for the mean monthly values published by Mr. Clayton in Smithsonian Miscellaneous Collections, vol. 77, No. 6, and in Table 53 of Volume IV of the Annals of the Astrophysical Observatory, for two reasons.

[3] The Mount Wilson solar constant values for 1919 and 1920 are taken here as they were in Tables 49 and 50 of Volume IV of the Annals of the Astrophysical Observatory of the Smithsonian Institution, for reasons stated on page 177 thereof.

[4] One is inclined to think from the results of both July and August that for some reasons the bolometric results of 1914 are about 1 per cent high throughout that year, a conclusion which is quite in line with their departure from what would be expected at that time of the sun-spot cycle. I have made a partial investigation of this question and find that the atmospheric transmission coefficients for the different wave lengths for 1914 were lower than would be expected for days of equal precipitable water for other years, and it is possible that we may be able to find why the results of this year are thus out of line

In the first place, present departures are given in percentages calculated severally from the general means of the three groups above described. Thereby the correction for sky brightness which I have just explained is eliminated.

In the second place, the mean monthly values given by Mr. Clayton and published in Volume IV of the Annals include all of the days, among them those of Group 4 which have been rejected in this discussion, for the reasons given above.

As stated by me in Smithsonian Miscellaneous Collections, vol. 77, No. 5, p. 3, I had supposed that the range of solar constant values given in the Annals for Mount Wilson was perhaps twice as great as the true one on account of the sources of error which I discussed there. This expectation is now confirmed, for it is seen that the range of results for the month of July given in Table 53 of Volume IV of the Annals is about double the range which is given in Figure 1 of the present paper.

TABLE 5.—*Proof of short-interval solar variation*

(Percentage deviations from monthly means for individual days)

Month	High values			Medium values			Low values		
	Number of days	Pyrh. mean	Solar constant mean	Number of days	Pyrh. mean	Solar constant mean	Number of days	Pyrh. mean	Solar constant mean
1910, July	2	2.58	1.68	2	−0.09	−0.47	2	−2.45	−1.05
1911	2	2.32	1.63	2	+0.18	−0.92	2	−2.40	−1.74
1914	1	1.38	0.10	1	0.00	−1.32	1	−1.41	+0.10
1915	4	1.69	0.52				4	−1.67	−0.84
1916	3	0.82	−0.09	2	+0.33	−0.11	3	−1.07	+0.14
1917	1	1.31	0.48				1	−1.31	−0.42
1918	3	1.28	0.82				3	−1.29	−0.86
1919	3.	0.87	−0.10				1	−2.65	+0.32
1920	2	0.59	0.16	2	−0.02	+0.10	1	−1.10	−0.41
1910, August	5	2.11	0.51				4	−2.67	−0.62
1911	6	1.71	0.91	3	+0.02	−0.24	10	−1.02	−0.46
1914	2	1.10	0.15	2	+0.11	−0.93	1	−2.42	+1.50
1915	6	0.87	0.16	3	−0.21	+0.33	5	−1.12	−0.45
1916	2	2.84	0.54				5	−1.16	−0.29
1917	3	0.97	0.69	1	+0.20	−0.36	2	−1.55	−0.13
1918	1	2.48	1.04	2	−0.09	−0.38	2	−1.29	−0.19
1919	3	0.73	0.02				1	−1.37	−0.10
1920	2	1.00	0.46				3	−0.67	−0.61
Total	51			20			51		
Weighted mean		+1.43	+0.51		+0.03	−0.34		−1.47	−0.42

I have used this new pyrheliometric method of consideration not only as furnishing evidence of long interval fluctuations of the solar radiation, but to determine whether short interval solar changes are also probably real. For this purpose I have confined myself to the values in Group 1 as having greater weight than the others. These values I have divided, in each month (July and August, 1910 to 1920) as between high, medium, and low. Medium values, however, are frequently absent. All of the days included in Table 1 are thus indicated by distinctive types, but though doubtless Groups 2 and 3 would show the phenomenon, I have, as stated above, employed only Group 1 in this study. I have set over against the pyrheliometry the solar constant values, E'_0, found on the same identical days. Obviously the range of pyrheliometry includes its errors and differences of conditions. Hence it must exceed the range of solar constant values for identical days whose errors may tend in opposite directions. In each instance I have determined the percentage departure from the mean of that group for that individual month, both of the pyrheliometry at air mass 1.5 and of the solar constant value E6.

In general, the two sets of data agree as showing which are the days of high and days of low solar constant. The monthly values and the mean of all the results are as given in Table 5.

From this, it seems to be indicated that not only did the solar constant vary in a close relation with the sunspot numbers during the months of July and August from 1910 to 1920 (excluding the years 1912 and 1913, which were not capable of treatment by the new method) but also that during this long period of time the high and low days for the months of July and August indicated themselves in the pyrheliometry quite as plainly as in the solar constant values published in Volume IV of the Annals, and on the whole in harmony therewith.

The pyrheliometric method which I have explained has some valuable applications and certain limitations, as shown in Table 5.

Advantages of the method.—1. It is direct, for it simply employs measurements of total radiation, without spectrum work except as an indication of atmospheric humidity.

2. It is competent to confirm the existence of solar variability both of long and short interval.

3. It furnishes means of testing whether the general scale of solar constant determinations remains unchanged over a period of years.

4. It will give new testimony as to the reality of certain apparent prolonged depressions of the solar constant, which, if real, are important.

Disadvantages of the method.—1. The pyrheliometric method can not be applied convincingly to treat long interval variations in years like 1912 and 1913 when the atmospheric transparency for equal humidity was abnormally low on account of volcanic dust.

2. It is unsatisfactory except for stations of very excellent and uniform conditions.

3. It is applicable to only a part of the cloudless days at any station, because on some days the relations between atmospheric humidity and transparency are so abnormal that such days fit none of the groups.

4. It is incapable of giving individual results. Differences between sky conditions of different days, even if small, produce differences of pyrheliometeric readings. These must be eliminated by taking means for many days.

5. In short, the method is not a substitute for the solar constant methods, but only supplementary to them.

We are going on to apply the new pyrheliometric method to Montezuma and Harqua Hala results from 1920 to 1925. In each of these stations the pyrheliometers were repeatedly compared with other instruments and seemed to furnish a perfectly homogeneous series of observations for discussion. Furthermore, the character of the sky, especially at Montezuma, is so much superior to that at Mount Wilson that we may expect even better results than have been found in the work thus far. It will be exceedingly interesting when this discussion is completed, to see if the great depression of the solar constant from about March, 1922, to the present time is verified, and it will be exceedingly valuable to assure ourselves that the scale of observations throughout the recent period has remained unchanged.

I hope soon to publish the results of such a study in the Smithsonian Miscellaneous Collections, and at that time to discuss more fully the influence of radiation from and toward the sky near the sun, and the influence of volcanic dust in solar constant values.